The University of Chicago

POLARIZATION OF HARD X-RAYS

A DISSERTATION SUBMITTED TO THE FACULTY OF THE DIVISION OF THE PHYSICAL SCIENCES IN CANDIDACY FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF PHYSICS

1937

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Polarization of Hard X-Rays

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(Received September 5, 1936)

A study has been made of the polarization of x-rays scattered at 90° from the primary beam for various voltages ranging from 80 to 800 kilovolts. The scattered rays were again scattered at 90° and a Geiger-Müller counter was used to determine the relative intensities of the tertiary rays in directions parallel and perpendicular to the primary rays. At 80 kilovolts the polarization was found to be practically complete, but it was found to decrease to 69.6 percent as the x-ray tube voltage was raised to 800 kilovolts. Within the limits of experimental error, the results agree with Nishina's theory which predicts an unpolarized component in the secondary x-rays increasing in relative magnitude as the frequency of the primary rays becomes greater.

INTRODUCTION

IN 1928 Klein and Nishina[1] published their well-known formula for x-ray scattering per electron. This formula was derived on the basis of the relativistic quantum mechanics of Dirac. Except in the domain of very short wave-lengths, the predictions of the Klein-Nishina formula differ very little from the predictions of the formula derived by Dirac[2] in 1926, or from those of the formula derived by Compton[3] in 1923. However, when the wave-length of the incident rays is sufficiently short that the mass of a photon of the rays is comparable with the rest mass of the scattering electron, the Klein-Nishina formula gives a scattering coefficient that is considerably greater than that from either of the other formulas. Recent experimental results by several investigators[4] have been in excellent agreement with the Klein-Nishina formula.

Besides predicting different results regarding intensity, there is another feature of the Klein-Nishina formula that differs from the other formulas. The latter require the rays scattered at 90° with the primary beam to be completely plane polarized. According to the Klein-Nishina formula, the rays scattered at 90° are not completely plane polarized, but contain an unpolarized component which is a function of the frequency. For ordinary wave-lengths the unpolarized component is negligible, but it becomes important at wave-lengths at which the intensity predictions of the Klein-Nishina formula begin to differ appreciably from those of the older theories. Dirac's theory shows that the electron has a property which may be interpreted as a magnetic moment, and it is this magnetic moment that leads to the unpolarized component.

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[1] O. Klein and Y. Nishina, Zeits. f. Physik **52**, 853 (1928).

[2] P. A. M. Dirac, Proc. Roy. Soc. **A111**, 405 (1926). Also derived independently by G. Breit, Phys. Rev. **27**, 362 (1926), and by W. Gordon, Zeits. f. Physik **40**, 117 (1926).

[3] A. H. Compton, Phys. Rev. **21**, 491 (1923).

[4] C. Y. Chao, Phys. Rev. **36**, 1519 (1930); J. Read and C. C. Lauritsen, Phys. Rev. **45**, 433 (1934); W. V. Mayneard and J. E. Roberts, Nature **136**, 793 (1935); J. Read, Proc. Roy. Soc. **A152**, 402 (1935); L. Meitner and H. Hupfeld, Zeits. f. Physik **67**, 147 (1930); G. B. T. Tarrant, Proc. Roy. Soc. **128**, 345 (1930).

A. H. Compton[5] notes that from purely classical electrodynamics there should be an unpolarized component if the electron has a magnetic moment. Nishina[6] has considered the polarization of the rays scattered at 90° and has derived an expression for the intensity of the rays after a second scattering at 90°. His result is

$$I_t = \frac{e^8}{2m^4c^8r^2r'^2}\frac{I_0}{(1+2\alpha)^3}\left[\sin^2\theta + \frac{\alpha^2(2+4\alpha+3\alpha^2)}{2(1+\alpha)^2(1+2\alpha)}\right],$$

where $\alpha = h\nu/mc^2$, I_t is the intensity of the tertiary rays, I_0 is the intensity of the primary rays, r is the distance between the two scattering electrons, r' is the distance from the second electron to the point of observation, θ is the angle measured in a plane at right angles to the direction of the secondary rays and is the angle between the direction of observation and a line perpendicular to the direction of the primary rays, and e, h, and ν have their usual meaning. The experiments described below were performed to test Nishina's theory of the unpolarized component.

Source of X-Rays

The large x-ray tube at Mercy Hospital was used as a source of hard x-rays. The use of this equipment was made possible through the kind permission of Dr. Henry Schmitz of Mercy Hospital. Experiments were performed with the large tube operating at voltages from 400 to 800 kilovolts with 10 ma tube current, and with a smaller x-ray tube also at the hospital operated at 200 kilovolts and 25 ma tube current.

Apparatus

A. Counter and circuits

As a means of measuring relative x-ray intensities, a Geiger-Müller counter was used. Several types of counters were tried. The one which worked best consisted of a small cylinder of thin copper with a fine tungsten wire coaxial with it and sealed off in a glass tube at a pressure of 12.5 cm of dry air. The copper cylinder was 3 cm long and 1 cm in diameter. The negative potential applied to the cylinder of the counter tube was supplied by a slightly modified form of the circuit described by Johnson and Street.[7] The impulses from the counter were amplified by a circuit essentially the same as that described by Locher.[8] The specially designed mechanical recorder was capable of responding to 70 impulses per second. Radium tests showed that for gamma-rays the counting rate was directly proportional to the intensity of the rays.

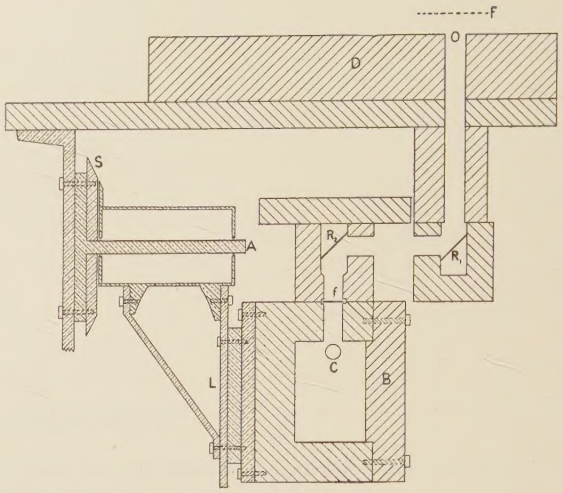

Fig. 1. Apparatus used in studying polarization.

B. Polarization apparatus

The apparatus used in studying the polarization is shown diagrammatically in Fig. 1. The counter tube C was inclosed in the lead box B having walls $1\frac{1}{2}$ inches thick. The lead box was rigidly attached to a steel beam L which could be rotated about the horizontal axis A. A divided circle S was used for angular measurements. A window in the x-ray tube permitted the x-rays to be emitted vertically downward, the target of the tube being surrounded with lead 6 inches thick except for the window. The apparatus was mounted under the x-ray tube so that the x-rays passed through the opening O and reached the counter after being scattered twice at right angles by the scatterers R_1 and R_2. The scatterers were of iron $1\frac{1}{2}$ mm thick and were set so that the incident rays struck them at 45°. The x-rays were filtered through the 3 mm brass window of the x-ray tube, through the filter at f consisting of 1 mm of aluminum and 0.5 mm of copper, the

[5] A. H. Compton and S. K. Allison, *X-Rays in Theory and Experiment* (1935), p. 237.
[6] Y. Nishina, Zeits. f. Physik **52**, 869 (1928).
[7] J. C. Street and T. H. Johnson, J. Frank. Inst. **214**, 155 (1932).
[8] G. L. Locher, J. Frank. Inst. **216**, 553 (1933).

aluminum being nearer the counter, and through additional filters placed at F. The additional filters ranged from 1 mm of aluminum at 400 kilovolts to 1 mm of aluminum, 3 mm of copper and 1 mm of tin at 800 kilovolts. The experimental arrangement with the 200 kilovolt tube was exactly the same, except that the filter at F consisted of 1 mm of aluminum and 0.75 mm of copper and the permanent filter in the window of the tube was different. A small metal box containing the first amplifying tube was attached to the side of the lead box containing the counter.

A large thickness of lead was required to protect the counter from the direct x-ray beam. With 1 inch of lead at D, the direct rays penetrated sufficiently to give 2500 counts per minute when the counter was in the horizontal position. In order to make the effect of the primary rays negligible, it was necessary to increase the thickness at D to $3\frac{1}{2}$ inches.

Experimental Procedure

Four readings were required to make a determination of the polarization. First a count was taken with the counter directly underneath the scatterer R_2. This is the position shown in the diagram. In this case the tertiary rays striking the counter were parallel to the primary rays. The lead box containing the counter was then swung through 90° into the horizontal position and a count taken. The scatterer R_2 was then taken out and counts taken in the two positions. These counts were subtracted from the first two to give net counts in the two positions. The average number of counts during 5 minute intervals as thus observed are given in Table I. Experiment showed that if the scatterer R_1 were removed instead of R_2, practically no radiation at all reached the counter, the counting rate in this case being less than one count per minute above the rate with the x-rays off. This showed that the radiation reaching R_2 that was not scattered from R_1 was negligible.

Table I. *Average number of counts during 5-minute intervals.*

Tube voltage kilovolts	Parallel		Perpendicular	
	R_2 in	R_2 out	R_2 in	R_2 out
200	2028	161	362	138
400	816	74	195	82
500	1090	95	275	92
600	1209	93	307	91
700	1466	113	408	103
800	1347	128	439	121

The counting rate throughout the experiments was sufficiently low to make it unnecessary to correct for impulses lost due to the resolving time of the apparatus. There were two sources of error that had to be taken into account. One resulted from multiple scattering and the other resulted from the fact that the rays were not all scattered at exactly 90°. The latter could be estimated from the geometry of the apparatus. An approximate calculation showed that this error amounted to about 4.5 percent, in the polarization. The multiple scattering error was estimated experimentally by using different thicknesses for the scatterers R_1 and R_2. This error was estimated to amount to about 6.5 percent.

The effective wave-length at each voltage was estimated from absorption measurements. With the counter tube set in the parallel position, the reduction in intensity due to different thicknesses of copper placed just above the filter F was determined. The effective mass-absorption coefficient was then computed. The value for the mass-absorption coefficient obtained in this way is too large because of strong absorption at the longer wave-lengths. An approximate correction for this error was estimated by using assumed spectral energy distributions in the primary beam. Such a correction, however, cannot be expected to be very accurate because of lack of knowledge of the exact spectral distribution.

Results

The polarization was computed from the defining relation

$$P=(I_{\parallel}-I_{\perp})/(I_{\parallel}+I_{\perp}),$$

where the net counts in the parallel and perpendicular directions were used for $I_{\parallel}$ and $I_{\perp}$, respectively. Table II shows the uncorrected and corrected values of the polarization. The results of the first series of experiments are relatively unreliable, due chiefly to lack of constancy of the x-ray tube. During the second series of experiments, referred to in Table II, the same counter tube was used throughout. No change could be detected in its residual count or in its response to

TABLE II. *Comparison of results with values calculated from Nishina's formula.*

X-ray tube voltage (kv)	Observed Polarization		Estimated wave-length A.U.	Corrected polarization results	Calculated from Nishina's formula
	1st series of experiments	2nd series of experiments			
	Percent	Percent		Percent	Percent
80	89.0	—	—	—	—
200	—	78.6	0.100	89.6	92.6
400	72.8	73.5	.060	84.5	84.2
500	63.9	68.9	.052	79.9	80.9
600	62.2	67.5	.050	78.5	80.0
700	60.8	63.2	.042	74.2	74.7
800	59.9	58.6	.039	69.6	73.1

radium tests throughout the period taken to do the experiments. Special precautions were also made to keep the x-ray tube operating under constant conditions. Due to the conditions under which the first set of results was obtained, they are not averaged with the results of the second set of experiments. The corrected results were obtained by adding a correction of 11 percent to each of the results of the second series of experiments. This is the estimated value for the two sources of error mentioned above. Each of the given experimental results represents an average of several separate trials. The value given for 80 kilovolts was obtained at Ryerson Laboratory with carbon scattering blocks before the apparatus was moved to the hospital. The corrected result at this voltage is not given because no effort was made to find the effect of multiple scattering in the carbon blocks. It would seem reasonable to assume that the correction in this case should be of the same order of magnitude as that at other voltages, and consequently the corrected result at this voltage should be approximately 100 percent. This would be in accord with earlier precision experiments on polarization, such as those of Compton and Hagenow.[9]

The last column in Table II gives the percentages of polarization predicted by Nishina's theory for the assumed wave-lengths. The estimated wave-lengths are rather uncertain, but they do not differ greatly from those which had previously been determined by Dr. Schmitz from absorption measurements in the primary beam. It is believed that these experiments furnish conclusive evidence that an unpolarized component of the predicted order of magnitude does exist.

The writer wishes to express his appreciation to Professor A. H. Compton for suggesting the problem and for much valuable advice, to Dr. Henry Schmitz of Mercy Hospital through whose cooperation this work was made possible, to the diagnostic x-ray department of Mercy Hospital for furnishing a room in which to keep the apparatus, and to Mr. F. W. Eims for many hours spent in operating the large x-ray tube.

[9] A. H. Compton and C. F. Hagenow, J. O. S. A. and R. S. I. **8**, 487 (1924).

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